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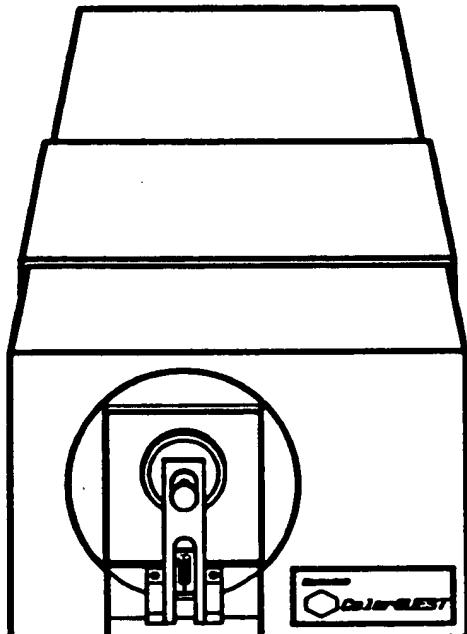
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HunterLab
ColorQUEST Sphere Spectrocolorimeter
Instruction Manual



Manual Version 1.4
July, 1992



Hunter Associates Laboratory, Inc.
11491 Sunset Hills Road
Reston, Virginia 22090-5280 U.S.A.
Tel.: (703) 471-6870
FAX: (703) 471-4237
Telex: 292821 HLAB UR

Measurement Values

Color values as measured on the ColorQUEST Sphere are relative to the absolute value of the perfect white diffuser as measured under the same geometric conditions (see ASTM Method E 306), according to the recommendation of the International Commission on Illumination, CIE, of January 1, 1969. These values are traceable to measurements made at the National Institute of Standards and Technology.

CIE Tristimulus XYZ Scale

The SpecWare software performs 5 nm weighted ordinate method tristimulus integration of reflectance values from 400 to 710 nm to arrive at tristimulus X, Y and Z values. These values simulate the color matching response functions of the human observer as defined by the 1931 2° Standard Observer or the 1964 CIE 10° Standard Observer. Tristimulus integrations based on any or all of the illuminants may be selected.

CIE Chromaticity Coordinates, Yxy

The relationship between CIE XYZ values and the x,y chromaticity coordinates is as follows:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

Opponent Color Scales (Hunter Lab - CIE 1976 L*a*b*)

The opponent color scales give measurements of color in units of approximate visual uniformity throughout the color solid. Thus, L measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it. The chromaticity dimensions (a and b) give understandable designations of color as follows:

a measures redness when plus, gray when zero and greenness when minus
b measures yellowness when plus, gray when zero and blueness when minus

The relationship between the Hunter Lab Scale and the CIE XYZ Scale for the CIE 1931 2° Standard Observer and the CIE 1964 10° Standard Observer for the eight illuminations are as follows:

$$L = 100 \sqrt{Y/Y_n}$$

$$a = K_a \frac{X/X_n - Y/Y_n}{\sqrt{Y/Y_n}}$$

$$b = K_b \frac{X/X_n - Y/Y_n}{\sqrt{Y/Y_n}}$$

where:

X, Y, Z are CIE tristimulus values.

X_n, Y_n, Z_n are tristimulus values of the standard illuminant as listed in Tables 1 and 2 with Y_n always equal to 100.00 (normalized).

K_a, K_b are chromaticity coefficients for the illuminant used.

Illuminant A represents incandescent lamplight with an approximate color temperature of 2854 K. Illuminant C represents light from an overcast sky with a correlated color temperature of approximately 6770 K. Illuminant D₆₅, D₅₀, D₆₀, D₇₅ represent daylight with a correlated color temperatures of approximately 6500 K, 5000 K, 6000 K and 7500 K respectively. Illuminant F2 represents light from a cool white fluorescent source.

Table 1
CIE 1931 2° Standard Observer
Standard Illuminant Tristimulus Values

| Illuminant | X _n | Z _n | K _a | K _b |
|-----------------|----------------|----------------|----------------|----------------|
| A | 109.83 | 35.55 | 185.20 | 38.40 |
| C | 98.04 | 118.11 | 175.00 | 70.00 |
| D ₆₅ | 95.02 | 108.82 | 172.30 | 67.20 |
| F2 | 98.09 | 67.53 | 175.00 | 52.90 |
| TL4 | 101.40 | 65.90 | 178.00 | 52.30 |
| UL 3000 | 107.99 | 33.91 | 183.70 | 37.50 |
| D ₅₀ | 96.38 | 82.45 | 173.51 | 58.48 |
| D ₆₀ | 95.23 | 100.86 | 172.47 | 64.72 |
| D ₇₅ | 94.96 | 122.53 | 172.22 | 71.30 |

Table 2
CIE 1931 10° Standard Observer
Standard Illuminant Tristimulus Values

| Illuminant | Xn | Zn | Ka | Kb |
|-----------------------|---------------|---------------|---------------|--------------|
| A | 111.16 | 35.19 | 186.30 | 38.20 |
| C | 97.30 | 116.14 | 174.30 | 69.40 |
| D₆₅ | 94.83 | 107.38 | 172.10 | 66.70 |
| F2 | 102.13 | 69.37 | 178.60 | 53.60 |
| TL4 | 103.82 | 66.90 | 180.10 | 52.70 |
| UL 3000 | 111.12 | 35.21 | 186.30 | 38.20 |
| D₅₀ | 96.72 | 81.45 | 173.82 | 58.13 |
| D₆₀ | 95.21 | 99.60 | 172.45 | 64.28 |
| D₇₅ | 94.45 | 120.70 | 171.76 | 70.76 |

The Hunter Lab total color difference (ΔE) and chromaticity difference (ΔC) for any illuminant or observer are calculated as follows:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

$$\Delta C = \sqrt{\Delta a^2 + \Delta b^2}$$

where:

$$\Delta L = L_{SMP} - L_{STD} \quad \begin{matrix} \text{(if } + \Delta L, \text{ sample is lighter than standard} \\ \text{if } - \Delta L, \text{ sample is darker than standard) } \end{matrix}$$

$$\Delta a = a_{SMP} - a_{STD} \quad \begin{matrix} \text{(if } + \Delta a, \text{ sample is redder than standard} \\ \text{if } - \Delta a, \text{ sample is greener than standard) } \end{matrix}$$

$$\Delta b = b_{SMP} - b_{STD} \quad \begin{matrix} \text{(if } + \Delta b, \text{ sample is yellower than standard} \\ \text{if } - \Delta b, \text{ sample is bluer than standard) } \end{matrix}$$

The ΔE derived from these opponent-color scales approximates the NBS Unit of Color Difference (Judd-Hunter), which represents the average maximum difference acceptable in a series of dye-house commercial matches in 1939.

The CIE 1976 L*a*b* Scale is recommended by the Commission Internationale de l'Eclairage (CIE). It is a simplified cube root version of the Adams-Nickerson space produced by plotting in rectangular coordinates the quantities of L*a*b*.

The relationship between the CIE L*a*b* scale and the CIE XYZ Scale for any illuminant reference in Tables 1 and 2 is as follows:

If all values of X/X_n, Y/Y_n, Z/Z_n > 0.008856, use the following:

$$L^* = 116 \sqrt[3]{Y/Y_n} - 16$$

$$a^* = 500 \left(\sqrt[3]{X/X_n} - \sqrt[3]{Y/Y_n} \right)$$

$$b^* = 200 \left(\sqrt[3]{Y/Y_n} - \sqrt[3]{Z/Z_n} \right)$$

If any value of X/X_n, Y/Y_n, Z/Z_n ≤ 0.008856, use the following:

$$L^* = 903.3 \frac{Y}{Y_n}$$

$$a^* = 500 [f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200 [f(Y/Y_n) - f(Z/Z_n)]$$

where:

$$f(X/X_n) = \sqrt[3]{X/X_n} \quad X/X_n > 0.008856$$

$$f(X/X_n) = 7.87(X/X_n) + 16/116 \quad X/X_n < 0.008856$$

$$f(Y/Y_n) = \sqrt[3]{Y/Y_n} \quad Y/Y_n > 0.008856$$

$$f(Y/Y_n) = 7.87(Y/Y_n) + 16/116 \quad Y/Y_n < 0.008856$$

$$f(Z/Z_n) = \sqrt[3]{Z/Z_n} \quad Z/Z_n > 0.008856$$

$$f(Z/Z_n) = 7.87(Z/Z_n) + 16/116 \quad Z/Z_n < 0.008856$$

where X_n, Y_n, Z_n are tristimulus values for any illuminant.

Total Difference (ΔE^*), CIE 1976 a,b Chroma-Differences (ΔC^*) and CIE 1976 a,b Hue Difference (ΔH^*).

$$\Delta E^* = \sqrt{\Delta L^*^2 + \Delta a^*^2 + \Delta b^*^2}$$

$\Delta C^* = C^*_{\text{smp}} - C^*_{\text{std}}$ where $C^* = \sqrt{a^*^2 + b^*^2}$ and is termed metric chroma

$$\Delta H^* = \sqrt{\Delta E^*^2 - \Delta L^*^2 - \Delta C^*^2}$$

ΔE^* is the same quantity as that described above, using CIE L*a*b* (CIELAB) values. It approximates the NBS Unit of Color Difference.

ΔC^* is the difference between the chroma of the sample and the chroma of the standard, as described in a polar coordinate system. Note that it is not the same quantity as the chromaticity difference ΔC .

ΔH^* describes the difference between the hue angle (h°) of the standard and the hue angle of the sample in a polar coordinate system, where:

If $h^\circ_{\text{smp}} > h^\circ_{\text{std}}$ then ΔH^* is regarded as positive
If $h^\circ_{\text{std}} > h^\circ_{\text{smp}}$ then ΔH^* is regarded as negative

See Recommendation on Uniform Color Spaces, Color Difference Equations, Psychometric Color Terms, Supplement No. 2 to CIE Publication No. 15 (E-1.3.1) CIE, Paris, 1978.

$$L^* = \text{CIE 1976 psychometric lightness} = 116 \sqrt[3]{Y/Y_n} - 16$$

$$a^* = \text{Red(+) - Green(-) axis} = 500 \left(\sqrt[3]{X/X_n} - \sqrt[3]{Y/Y_n} \right)$$

$$b^* = \text{Yellow(+) - Blue(-) axis} = 200 \left(\sqrt[3]{Y/Y_n} - \sqrt[3]{Z/Z_n} \right)$$

$$C^*_{ab} = \text{CIE 1976 a,b chroma} = \sqrt{a^*^2 + b^*^2}$$

$$h^\circ = \text{CIE 1976 a,b hue-angle} = \arctan(b^*/a^*)$$

$$\Delta H^*_{ab} = \text{CIE 1976 a,b hue-difference} = \sqrt{\Delta E^*^2 - \Delta L^*^2 - \Delta C^*^2}$$

$$\Delta C = \text{Chromaticity difference in a*b* plane} = \sqrt{\Delta a^*^2 + \Delta b^*^2}$$

$$\Delta E^*_{ab} = \text{CIE 1976 L*a*b* color difference formula} = \sqrt{\Delta L^*^2 + \Delta a^*^2 + \Delta b^*^2}$$

Δ = Difference between Sample and Standard

Reference: Commission International de l'Eclairage (CIE): Recommendations on Uniform Color Spaces, Color Difference Equations, Psychometric Color Terms, Supplement No. 2 to CIE Publication No. 15, Colorimetry, Bureau Central de la CIE, Paris, 1978.

Hunter Rdab Color Scale

The relationship between the Hunter $R_{d,a,b}$ values and the CIE XYZ values for any illuminant (see Tables 1 and 2) is as follows:

$$R_d = Y$$

$$a_{Rd} = K_a f(Y) \left(\frac{X}{X_n} - \frac{Y}{Y_n} \right)$$

$$b_{Rd} = K_b f(Y) \left(\frac{Y}{Y_n} - \frac{Z}{Z_n} \right)$$

where

$$f(Y) = 0.51 \frac{21 + 0.2 Y}{1 + 0.2 Y}$$

See Tables 1 and 2 for values of K_a , K_b , X_n , and Z_n . Y_n is always equal to 100.00.

Adams - Nickerson (AnLab)

When the instrument is equipped with this scale, the optimal feature provides a readout of AnLab values. The relationship between the Adams-Nickerson (AnLab) Scale and the CIE XYZ Scale for Illuminant C is as follows:

$$L = 9.2 V_y$$

$$a = 40 (V_x - V_y)$$

$$b = 16 (V_y - V_z)$$

Where V represents the Munsell value function for which X/X_n , Y/Y_n or $Z/Z_n = 1.2219V - 0.23111V^2 + 0.23951V^3 - 0.021009V^4 + 0.0008404V^5$.

CMC

The equation for $\Delta E_{CMC} < 1$ describes an ellipsoidal volume, with axes in the direction of lightness and chroma and hue centered about a standard. When the semi-axes lengths for the ΔE_{CMC} formula equal the calculated ISL, cSC, and SH values for the standard, the resulting ellipsoid describes a 1.0 ΔE_{CMC} unit volume/tolerance. This volume, and the size of its component parts become the basis for the establishment of an appropriately sized volume of acceptability for a given commercial situation by the application of a commercial factor (cf).

When $l = 2.0$ and $c = 1.0$, the equation fixes the ratio of the three components (SL:SC:SH:) to correlate with visible assessment of typical textile samples. Other values of l may be required in cases where the surface characteristics change dramatically. The value of c is always left at 1.0.

$$\Delta E_{CMC} = \sqrt{(\Delta L^*/ISL)^2 + (\Delta C^*/cSC)^2 + (\Delta H^*/SH)^2} \quad \text{Absolute}$$

$$\Delta L_{CMC} = \frac{\Delta L^*}{ISL}$$

$$\Delta C_{CMC} = \frac{\Delta C^*}{cSC}$$

$$\Delta H_{CMC} = \frac{\Delta H^*}{SH}$$

$$\Delta E_{CMC} \text{ cf (l:c)} = \frac{1}{cf} \Delta E_{CMC} \quad \text{Normalized}$$

$$\Delta L_{CMC} = \frac{\Delta L^*}{(cf) ISL}$$

$$\Delta C_{CMC} = \frac{\Delta C^*}{(cf) cSC}$$

$$\Delta H_{CMC} = \frac{\Delta H^*}{(cf) SH}$$

where

L^* , C^* , and H^* are those of the standard unless otherwise specified.

CMC ratio l:c

commercial factor cf

$$SL = \frac{0.040975L^*}{1 + 0.01765L^*} \quad \text{for } L^* > 16$$

$$SL = 0.511 \quad \text{for } L^* < 16$$

$$SC = \frac{0.0638 C^*}{1 + 0.0131 C^*} + 0.638$$

$$SH = (FT + 1 - F) SC$$

$$C^* = \sqrt{\Delta a^*{}^2 + \Delta b^*{}^2}$$

$$h^{\circ} = \arctan(b^*/a^*)$$

$$\Delta L^* = L^*_{SMP} - L^*_{STD}$$

$$\Delta C^* = C^*_{SMP} - C^*_{STD}$$

$$\Delta H^* = \sqrt{\Delta E^*^2 - \Delta L^*^2 - \Delta C^*^2}$$

$$F = \sqrt{C^*^4 / (C^*^4 + 1900)}$$

$$T = 0.36 + |0.4 \cos (35 + h) |$$

for $h, 164^\circ$ or $h > 345^\circ$

$$T = 0.56 + |0.2 \cos (168 + h) |$$

for $164^\circ < h < 345^\circ$

Tolerances are:

$$\begin{aligned}\Delta L^* &= (cf) ISL \\ \Delta C^* &= (cf) cSC \\ \Delta H^* &= (cf) SH\end{aligned}$$

| | <u>Absolute</u> | <u>Normalized</u> |
|------------------|-----------------|-------------------|
| ΔL_{CMC} | = cf | = 1 |
| ΔC_{CMC} | = cf | = 1 |
| ΔH_{CMC} | = cf | = 1 |
| ΔE_{CMC} | = cf | = 1 |

For a more detailed description of CMC, refer to *Calculation of Small Color Differences for Acceptability*, AATCC Test Method 173-1989 published in AATCC Technical Manual.

FMC-2 (Friele - MacAdam - Chickering) Color Difference

Red-green (RG) differences, yellow-blue (YB) differences, total lightness differences (DL) and total color differences (DE) between standard and sample are computed according to the Friele-MacAdam-Chickering metric (JOSA, February 1968, p.292 and August 1969, p.986).

The FMC-2 unit of color difference is based on just noticeable, or threshold, color difference data published in 1942. Friele used the data in his suggested color-difference formula, which was modified later by MacAdam, and then by Chickering. The FMC-2 Scale is a color difference scale only and was designed for Illuminant C and 2° standard observer conditions only. It has been successfully used for non-saturated colors under illuminants D₆₅ and A as well as 10° standard observer conditions.

Metamerism Index

The Metamerism Index is designed to indicate the degree to which 2 samples which match under 1 illuminant no longer match under a 2nd illuminant. The metamerism index feature allows the comparison of Hunter Lab values relative to operator selectable illuminants. These values must be calculated from spectral reflectance values. The formula for deriving the index is:

$$MI = \sqrt{(\Delta L_{n1} - \Delta L_{n2})^2 + (\Delta a_{n1} - \Delta a_{n2})^2 + (\Delta b_{n1} - \Delta b_{n2})^2}$$

where n1 is the 1st illuminant and n2 is the 2nd illuminant.

Opacity Measurements

Opacity measurements determine opacity by a contrast ratio measurement. The Y value of the specimen backed by the black glass or light trap is divided by the Y value of the specimen backed by the white tile. The resulting fraction is Y% or opacity.

$$\text{Opacity} = \frac{Y_{\text{black backing}}}{Y_{\text{white backing}}}$$

Haze Measurements

A transmission haze measurement is a ratio of the diffuse light to the total light transmitted by a specimen. Useful measurements of haze can be made on the ColorQUEST sphere although the results do not conform to ASTM method D1003, because of differences in instrument geometry.

$$\text{Haze} = \frac{\text{diffuse transmittance}}{\text{total transmittance}} \times 100$$

Whiteness Index

Whiteness is associated with a region or volume in color space in which objects are recognized as white. Degree of whiteness is measured by the degree of departure of the object from a *perfect* white.

Whiteness Index per ASTM E313 (displayed as WI E313):

$$WI\ E313 = \frac{4\ Z_{CIE}}{1.18103} - 3Y = 4\ Z\% - 3Y$$

Yellowness Index

Visually, yellowness is associated with scorching, soiling and general product degradation by light, chemical exposure and processing. Yellowness indices are used chiefly to measure these types of degradation.

Yellowness Index per ASTM Method D1925-70* (displayed as YI D1925):

$$YI\ D1925 = \frac{100(1.274641506\ X - 1.057434092\ Z)}{Y}$$

*The YI formula, as shown in ASTM D1925-70, is:

$$YI\ D1925 = \frac{100(1.28\ X_{CIE} - 1.06\ Z_{CIE})}{Y_{CIE}}$$

The tristimulus values of clear air (for CIE illuminant C and the 1931 CIE 2° standard observer) are $X = 98.041$, $Y = 100.000$, $Z = 118.103$. ** The ASTM formula gives $YI = 0.303$ for clear air, because the factors are truncated to 3 significant figures. In order to have the yellowness index for air equal to 0.0, the constant multipliers for X_{CIE} and Z_{CIE} have been expanded slightly. Work is in progress in ASTM to revise the test method accordingly.

** Wyszecki, G. and W. S. Stiles, *Color Science*, John Wiley and Sons, New York, 1982 - p. 768.

Yellowness Index per ASTM Method E313 (displayed as YI E313):

$$YI\ E313 = 100 \left(1 - \frac{B}{G} \right) = 100 \left(1 - \frac{0.847\ Z}{Y} \right)$$

APHA-20 mm

APHA-20 mm is designed to yield APHA values that closely correlate to APHA standard solutions as defined by ASTM D1209. APHA-20 mm is calculated from the YI D1925 yellowness index using the following equation:

$$\text{APHA-20 mm} = K_1 + K_2 (\text{YI D1925}) + K_3 (\text{YI D1925})^2 + K_4 (\text{YI D1925})^3$$

The constants are defined according to the value for YI D1925.

The values for the constants along with an upper bound for each range may be specified in an ASCII file APHA20.DAT. This file may be created by the user. If the file is not created the default values given in Table 3 are used.

Table 3

| Upper Bound for YI-D1925 | K₁ | K₂ | K₃ | K₄ |
|-------------------------------------|----------------------|----------------------|----------------------|----------------------|
| 3.0 | 0.000000 | 9.063781 | 0.000000 | 0.000000 |
| 50.0 | 4.369262 | 7.825047 | 0.071435 | -0.000158 |
| 1000.0 | 4.369262 | 7.825047 | 0.071435 | -0.000158 |

Paper Brightness - Z%

Paper brightness or Z% is used in the evaluation of the degradation of white materials. It can also be a measure of the effectiveness of bleaching.

$$Z\% = \frac{100 Z_{\text{CTE}}}{Z_a}$$

457 nm Brightness

457 nm brightness can also be used to measure the relative brightness of paper. 457 nm brightness reports the percent reflectance at 457 nm.

Dominant Wavelength and Excitation Purity

The dominant wavelength and excitation purity chromaticity system was one of the first systems for specifying the chromaticity of objects other than by their x, y values. It not only compensates for the influence of the illuminant's chromaticity, but also improves the correlation between the numbers and visual attributes because it permits chromaticity specification in terms of hue and saturation. The system is based on the additive-color-mixing properties of the x,y diagram. A color is specified by describing how it would be matched by additively mixing the illuminant and light of some single wavelength.

Dominant wavelength is the wavelength needed for mixture with the illuminant. In general, it identifies the hue of the object's color.

Excitation purity is the percentage contribution of the dominant wavelength to the mixture. Thus, 1.00 is the purity of all spectral colors and 0 is the purity of the illuminant. Excitation purity correlates with saturation.

In order to derive dominant wavelength and excitation purity for a sample, plot the position of the illuminant C - object color combination on the CIE x,y chromaticity diagram. The dominant wavelength for sample (S) under illuminant C is found by drawing a straight line from the Illuminant C point through S to the spectrum locus, where it intersects at the dominant wavelength. Excitation purity is the percentage of the distance from illuminant C to S compared to the total distance from illuminant C to the spectrum locus.

Dominant wavelength and excitation purity are calculated for the wavelengths of 397-673 nm. These values are always calculated and displayed relative to the CIE 1931 2° standard observer and CIE illuminant C regardless of the selected illuminant and observer. For complementary wavelengths, the displayed values are 0.

For further information see *A Digital Computer Technique for Calculation of Dominant Wavelength* by Charles G. Leete and Jack R. Lytle in *Color Engineering*, Volume 4, No. 1 (January - February 1966).

K/S and Relative Colorant Strength

Selecting K/S + COLORANT STRENGTH in the spectral data setup screen results in K/S and colorant strength calculations in the reflectance mode and absorbance and percent dye strength in the transmittance mode.

K/S values for the product standard and sample are calculated for all wavelengths. The point of minimum reflectance or maximum absorption of the product standard is highlighted. This method of strength calculation is most accurate when the standard and sample are chemically and physically identical and differ only in depth. The sample strength should not be more than $\pm 20\%$ that of the standard. If the strength difference is substantially larger than 20%, prepare the sample in a new concentration so that it falls within the $\pm 20\%$ interval where the Kubelka-Munk relationship is more nearly linear. This calculation is valid only for reflectance measurements. As in any test procedure, the statistical benefits of averaging data of multiple measurements should be considered.

The formula for calculation of percent strength in terms of percent of standard is as follows:

$$\frac{K}{S} = \frac{[1 - 0.01 R]^2}{2[0.01 R]} \quad \text{where } R = \text{reflectance}$$

$$\text{Relative Color Strength (\% of Standard)} = \frac{K/S_{\lambda \text{ samp}}}{K/S_{\lambda \text{ std}}} \times 100 \quad \text{where } \lambda = \text{wavelength}$$

The relative effectiveness of a batch of a given colorant for generating the desired chromaticity and depth in a given formulation is frequently termed *relative color strength* and is calculated as shown above. This evaluation of strength is based on reflectance measurements using the Kubelka-Munk relationship between the diffuse reflectance (R) of the product standard, and the ratio of spectral absorption (K) to spectral scattering (S).

Absorbance and Percent Dye Strength

Absorbance values for the product standard and the sample are calculated for all wavelengths. The point of minimum transmittance or maximum absorbance of the standard is highlighted over the wavelength range specified in the global setup.

Industries using dyes may calculate percent strength of a dye in solution, relative to a standard, as a method of quality control of incoming dyes, or as an indication of how much additional dye, if any, is needed to bring the shade of a dyeing to the required depth. Relative dyestrength in terms of percent of standard may be determined by preparing solutions of the sample and of the standard as indicated in the reference below.

For further information, refer to *A General Procedure for the Determination of Relative Dye Strength by Spectrophotometric Transmittance Measurement* by Problem Committee 25 (Dyes) of the Inter-Society Color Council (ISCC), Rolf G. Kuhni, Co-Chairman, Textile Chemist and Colorist, Vol. 4, no. 5, May 1972, p.133.

The formula for calculation of dye strength in terms of percent of standard is as follows:

$$ABS = -\log_{10} T \quad \text{where } ABS = \text{absorbance and } T = \text{transmittance.}$$

$$\text{Dye Strength (\% of standard)} = \frac{ABS_{\text{samp}}}{ABS_{\text{std}}} \times 100$$

where ABS_{samp} is absorbance of a sample and ABS_{std} is absorbance of the standard.

Optical Density

In the fields of photography and graphic arts, colorants are frequently characterized by density measurements for their light absorbing ability in specific regions of the spectrum. Neutral density values are based on equal weighting of all wavelengths. Red, green and blue density values are based on specific spectral response functions designed to measure the quantity of dye colorants in photographic and printing materials. For further information, refer to "Objectives and Methods of Density Measurements in Sensitometry of Color Films," F. C. Williams, Journal of the Optical Society of America, Vol. 40, No. 2, February 1950.

The formula for calculation of optical density values from the spectral values is as follows.

For reflectance:

$$OpD = -\log_{10} R \quad \text{where } OpD = \text{reflection optical density, and } R = \text{reflectance.}$$

The relationship between optical density and reflectance is a log-reciprocal one. Therefore, increasing density values denote increasing obstruction to reflecting or transmitting light. In this attenuating effect, the density values are the exponent of 10. Therefore, a density of 3.0 means that 1/1000 of the light has been transmitted or reflected.